

keV scale ν_R dark matter and its detection in β decay experiment

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We study dark matter(DM) in the model with one keV scale right-handed neutrino ν_{R1} and two GeV scale right-handed neutrinos $\nu_{R2,3}$, the ν SM. We find that one of the GeV scale right-handed neutrinos can have much longer lifetime than the other when two GeV scale right-handed neutrinos are degenerate. We show that mass and mixing of light neutrinos can be explained in this case. Significant entropy release can be generated in a reheating produced by the decay of one of the GeV scale ν_R . The density of ν_{R1} DM can be diluted by two orders of magnitude and the mixing of ν_{R1} with active neutrinos is allowed to be much larger, reaching the bound from X-ray observation. This mixing can lead to sizeable rate of ν_{R1} capture by radioactive nuclei. The ν_{R1} capture events are mono-energetic electrons with keV scale energy away from the beta decay spectrum. This is a new way to detect DM in the universe.

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Introduction: Among many models of DM candidate a seesaw type model, the ν SM, is of particular interests [1]. In this model there is one keV scale right-handed neutrino ν_{R1} and two GeV scale right-handed neutrinos $\nu_{R2,3}$. The keV scale ν_{R1} has a lifetime longer than the age of the universe and is a DM candidate. One of the virtue of this model is that the DM particle is already introduced in seesaw mechanism for explaining the tiny masses of active neutrinos.

One interesting implication of ν_{R1} DM is that ν_{R1} can interact with Standard Model(SM) particles through small mixing with active neutrinos and it might be detected in laboratory experiments. However it was shown by some authors [2] that astrophysical constraints and the constraints from the mass and mixing of light active neutrinos are very

strong. Mixing of ν_{R1} with active neutrinos is very small and detecting ν_{R1} in laboratory experiment seems difficult. In this article we investigate the mixing of ν_{R1} and its density in the thermal history of the early universe. We show that relatively large mixing of ν_{R1} with active neutrinos is allowed in the ν SM when two GeV scale $\nu_{R2,3}$ are degenerate. We study the direct detection of the cosmic background of this keV scale ν_{R1} DM in beta decay experiment. In the following we briefly describe the ν SM and discuss issues related to DM. We study the mixing of light neutrinos with heavy neutrinos in the case that two GeV scale right-handed neutrinos are degenerate. We analyze the capture of the cosmic background of ν_{R1} DM in target of radioactive nuclei ^3H and ^{106}Ru .

keV scale ν_{R1} DM in ν SM: In seesaw mechanism mass matrix of active neutrinos is given by

$$m_\nu = v^2 Y^* M_R^{-1} Y^\dagger, \quad (1)$$

where M_R is the Majorana mass matrix of right-handed neutrinos, Y the matrix of Yukawa couplings, v the vacuum expectation value of doublet Higgs in the SM: $\langle H \rangle = (0, v)^T$. In seesaw mechanism Y can be parameterized as [3]

$$Yv = U(\tilde{m}_\nu)^{1/2} P^{1/2} O(M_R^*)^{1/2}, \quad (2)$$

where $\tilde{m}_\nu^{1/2} = \text{diag}\{m_1^{1/2}, m_2^{1/2}, m_3^{1/2}\}$ and $P^{1/2} = \text{diag}\{e^{i\phi_1/2}, e^{i\phi_2/2}, e^{i\phi_3/2}\}$. Real numbers $m_i (i = 1, 2, 3)$ are the masses of light neutrinos and $\phi_i (i = 1, 2, 3)$ are Majorana phases. $(M_R^*)^{1/2} = \text{diag}\{(M_1^*)^{1/2}, (M_2^*)^{1/2}, (M_3^*)^{1/2}\}$. U is the neutrino mixing matrix observed in neutrino oscillation experiments. O is a complex orthogonal matrix: $O^T O = O O^T = 1$.

Active neutrinos mix with heavy Majorana neutrinos through a mixing matrix

$$R = Yv(M_R^*)^{-1}. \quad (3)$$

Using Eq. (2) R is rewritten as

$$R = U(\tilde{m}_\nu)^{1/2} P^{1/2} O(M_R^*)^{-1/2}. \quad (4)$$

For convenience we will work in the base that $M_{1,2,3}$ are real.

keV scale ν_{R1} can decay to light active neutrinos or photon and its main decay channel is the decay to three active neutrinos. For $\theta_1^2 = \sum_l |R_{l1}|^2 \sim 10^{-8}$ the lifetime of ν_{R1}

is estimated $\sim 10^{21}$ s [1] which is much larger than the age of the universe $\sim 10^{17}$ s and long enough for a DM candidate. ν_{R1} DM can be produced in the early universe through active-sterile neutrino oscillation [1, 4–6]. For $\theta_1^2 \sim 10^{-8}$ significant amount of keV scale ν_{R1} can be produced. With larger mixing ν_{R1} DM can be over-produced using this mechanism. Many other aspects of this model of DM, e.g. constraints from X-ray observation and Lyman- α forest, detection of this DM, possible symmetries etc., have been analyzed [7–15]. Suggestions beyond the minimal model have also been made and other DM production mechanism has been considered [16–20].

ν_{R1} density can be diluted in the early universe and θ_1^2 is allowed to be much larger if significant entropy release is produced in a reheating at MeV temperature scale before the Big Bang Nucleosynthesis(BBN). This can be achieved by the decay of a non-relativistic particle in the early universe. It's interesting that GeV scale right-handed neutrino is a candidate of this non-relativistic particle. However it was noticed that this is a further constraint on the seesaw mechanism and large enough entropy production can not be obtained because of the constraint from mass and mixing of light neutrinos [2]. In the following we show that the analysis in [2] does not really apply to the case when two GeV scale right-handed neutrinos are degenerate ($M_3 = M_2$) and $\theta_1^2 \gg 10^{-8}$ is indeed allowed.

Entropy production by GeV scale ν_R and neutrino mixing: Using an explicit example we show that mass and mixing of light neutrinos and enough entropy production by the decay of a GeV right-handed neutrino can all be accommodated in ν SM when two GeV scale right-handed neutrinos are degenerate.

Two degenerate right-handed neutrino states can be rewritten in other base using a unitary transformation:

$$\begin{pmatrix} \nu'_{R1} \\ \nu'_{R2} \\ \nu'_{R3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c & -s \\ 0 & s^* & c^* \end{pmatrix} \begin{pmatrix} \nu_{R1} \\ \nu_{R2} \\ \nu_{R3} \end{pmatrix}, \quad (5)$$

where $|c|^2 + |s|^2 = 1$. The symmetric mass matrix M'_R in this base is no longer diagonal. We note that two states $|\nu'_{R2,3}\rangle$ have the same mass of $|\nu_{R2,3}\rangle$. This is just another way to write the mass term. For example, if $c = 1/\sqrt{2}$ and $s = i/\sqrt{2}$, M'_R is obtained (up to

a phase factor i) as

$$M'_R = \begin{pmatrix} M_1 & 0 & 0 \\ 0 & 0 & M_2 \\ 0 & M_2 & 0 \end{pmatrix}. \quad (6)$$

In Eq. (6) M_2 is written in the form of Dirac type. Another way to see this point is to note that $M_R M_R^\dagger$ and $M_R^\dagger M_R$ are not changed by Eq. (5) when $M_3 = M_2$. Hence Eq. (5) does no change the energy dispersion although M_R is transformed by it.

When $\nu_{R2,3}$ are degenerate we should transform them to interaction base to understand their interaction with active neutrinos. In the interaction base of $\nu'_{R2,3}$ Y' is obtained from Y : $Y' = YV^\dagger$ where V is the unitary matrix in $\nu'_R = V\nu_R$ as shown in Eq. (5). In the interaction base $Y'^\dagger Y'$ is obtained from $Y^\dagger Y$ to the following form

$$Y'^\dagger Y' = \begin{pmatrix} y_1^2 & y_{12}^2 & y_{13}^2 \\ y_{12}^{2*} & y_2^2 & 0 \\ y_{13}^{2*} & 0 & y_3^2 \end{pmatrix}. \quad (7)$$

Coupling of $\nu'_{R2,3}$ with active neutrinos are $y_{2,3}$ times active neutrino mixing.

As an example, we consider normal mass hierarchy and matrix O of the following form

$$O = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_\theta & s_\theta \\ 0 & -s_\theta & c_\theta \end{pmatrix}, \quad (8)$$

where $c_\theta = \cos \theta$, $s_\theta = \sin \theta$ and $\theta = x + iy$. x and y are real numbers. Diagonalizing the second and third entries of $Y^\dagger Y$ using Eq. (5) we obtain $c = \cos \alpha$, $s = \sin \alpha e^{i\beta}$ where

$$\tan 2\alpha = -\frac{2D}{A-B}, \quad (9)$$

$$De^{i\beta} = (m_2 c_\theta^* s_\theta - m_3 s_\theta^* c_\theta) M_2^{1/2} M_3^{1/2}, \quad (10)$$

and $D = |(m_2 c_\theta^* s_\theta - m_3 s_\theta^* c_\theta) M_2^{1/2} M_3^{1/2}|$, $A = M_2(m_2 |c_\theta|^2 + m_3 |s_\theta|^2)$, $B = M_3(m_2 |s_\theta|^2 + m_3 |c_\theta|^2)$. Three eigenvalues are found: $y_1^2 = m_1 M_1/v^2$,

$$y_2^2 = \frac{2C/v^2}{A+B+\sqrt{(A+B)^2-4C}}, \quad (11)$$

$$y_3^2 = \frac{1}{2v^2}(A+B+\sqrt{(A+B)^2-4C}) \quad (12)$$

where $C = m_2 m_3 M_2 M_3$.

For $|y| \gg 1$ it's easy to see that $|c_\theta| \approx |s_\theta| \approx \frac{1}{2}e^{|y|}$, $A \approx \frac{1}{4}M_2(m_2 + m_3)e^{2|y|}$, $B \approx \frac{1}{4}M_3(m_2 + m_3)e^{2|y|}$ and we find

$$y_2^2 \approx \frac{4C/v^2}{(m_2 + m_3)(M_2 + M_3)}e^{-2|y|}, \quad (13)$$

$$y_3^2 \approx \frac{1}{4v^2}(m_2 + m_3)(M_2 + M_3)e^{2|y|} \quad (14)$$

For normal mass hierarchy we have $m_3 \approx \sqrt{\Delta m_{atm}^2} \approx 0.05$ eV, $m_2 \approx \sqrt{\Delta m_{solar}^2} \approx 0.009$ eV and $m_1 \ll m_2$. Using $M_3 = M_2$ we get

$$y_2^2 \approx \frac{2m_2 M_2}{v^2}e^{-2|y|}, \quad y_3^2 \approx \frac{m_3 M_2}{2v^2}e^{2|y|}. \quad (15)$$

In Eq. (15) we see that coupling of ν'_{R2} with active neutrinos are suppressed by $e^{-|y|}$ if $|y|$ is large and coupling of ν'_{R3} is enhanced. We note that $\cos 2\alpha \rightarrow 0$, $|\beta| \rightarrow \pi/2$ in the limit $|y| \rightarrow \infty$ and the mass matrix M'_R approaches the mass matrix shown in Eq. (6).

The mixing R' in the interaction base can be similarly obtained. We obtain $\theta_{1,2,3}'^2 = \sum_l |R_{l1,l2,l3}'^2|^2$ as

$$\theta_1'^2 = \frac{m_1}{M_1}, \quad (16)$$

$$\theta_2'^2 \approx \frac{2m_2}{M_2}e^{-2|y|}, \quad (17)$$

$$\theta_3'^2 \approx \frac{m_3}{2M_2}e^{2|y|}. \quad (18)$$

The decay rate of ν'_{R2} (for $M_2 < M_W$) is [2]

$$\Gamma = \frac{G_F^2 M_2^5}{192\pi^3} F \theta_2'^2 \approx \frac{G_F^2 m_2 M_2^4}{96\pi^3} F e^{-2|y|}, \quad (19)$$

where a factor 2 has been included to account for the charge conjugation processes and a factor 1/2 has been included to account for the Majorana nature of ν'_{R2} . F is a factor which accounts for effects of various final states [2]. $F \approx 16.0$ for $m_b \ll M_2 < M_W$. The lifetime of ν'_{R2} is

$$\tau \approx 0.44 \text{ s} \times \frac{e^{2|y|}}{(2000)^2} \frac{0.01 \text{ eV}}{m_2} \left(\frac{30 \text{ GeV}}{M_2} \right)^4. \quad (20)$$

It is worth pointing out that ν'_{R2} can not decay through oscillation to ν'_{R3} because the probability of oscillation to ν'_{R3} vanishes when $\nu'_{R2,3}$ are degenerate. The above analysis

and the later discussions can also be applied to quasi-degenerate $\nu_{R2,3}$ if their mass difference is so small that no significant oscillation can happen before ν'_{R2} decays. For our whole discussion to be valid for quasi-degenerate $\nu_{R2,3}$, it's sufficient to assume that no significant oscillation can happen before the BBN time which is ~ 1 s. This condition is $|M_2 - M_3| \times 1 \text{ s} \ll \hbar$, or $|M_2 - M_3| < 6.58 \times 10^{-22} \text{ MeV}$.

Assuming that ν'_{R2} is in thermal equilibrium at very high temperature and decouples when it is relativistic, the entropy release produced by the decay of ν'_{R2} is [21]

$$\begin{aligned} S &\approx 0.76 \frac{g_N}{2} \frac{\bar{g}_*^{1/4} M_2}{g_* \sqrt{\Gamma M_{Pl}}} \\ &\approx 96 \times \left(\frac{0.01 \text{ eV}}{m_2} \right)^{1/2} \left(\frac{30 \text{ GeV}}{M_2} \right) \times \frac{e^{|y|}}{2000}, \end{aligned} \quad (21)$$

where $S = s_f/s_i$. s_f and s_i are entropies just after and before the decay of ν'_{R2} . $g_N = 2$ is the number of degrees of freedom of ν'_{R2} . g_* is the effective number of degrees of freedom at ν'_{R2} freeze-out which is assumed at electro-weak scale. $g_* \approx 101.5$ when excluding top quark. $\bar{g}_* \approx 10.75$ is the effective number of degrees just after the entropy release.

In Eq. (21) we can see that $S \sim 100$ can be achieved for $e^{|y|} \sim 2000$. According to Eq. (20), for this range of parameter space ν'_{R2} has lifetime $\lesssim 1$ s. So it decays before the BBN and does not spoil the prediction of the BBN [22]. It's also easy to see that without $e^{|y|}$ factor $M_2 \ll 1 \text{ GeV}$ is needed to make S larger than 100. However, $M_2 \ll 1 \text{ GeV}$ is not allowed because it would give a too long lifetime to ν'_{R2} and it would spoil the prediction of the BBN. We emphasize that previous negative conclusion on the entropy production by ν_{R2} [2] does not apply to the case we are considering. They worked in the base that mass matrix is diagonalized and did not pay attention to the fact that we should analyze the interaction of GeV scale right-handed neutrinos in their interaction base when they are degenerate.

We point out that in our example $\theta_1'^2 \sim 10^{-6}$ can be obtained by taking $m_1 \sim 10^{-3} \text{ eV}$ which is allowed by the neutrino oscillation experiments. Astrophysical observation of the decay $\nu_{R1} \rightarrow \nu \gamma$ is able to constrain $\theta_1'^2$ [23]

$$\theta_1'^2 \lesssim 1.8 \times 10^{-5} \left(\frac{1 \text{ keV}}{M_1} \right)^5. \quad (22)$$

We see that $M_1 \lesssim 2 \text{ keV}$ is needed for $\theta_1'^2$ reaching $\sim 10^{-6}$. M_1 is constrained by the observation of dwarf spherical galaxies: $M_1 \gtrsim 1 - 2 \text{ keV}$ [11]. M_1 is also constrained by

Lyman- α forest. In the case we are considering the Lyman- α bound is $M_1 \gtrsim 1.6$ keV when $S \approx 100$ [2] which is re-scaled by a factor $S^{-1/3}$ compared to the bound for non-resonant production of ν_{R1} DM [10]. We further note that X-ray and Lyman- α [10] constraints become weaker when ν_{R1} DM accounts for part of the DM in the universe, e.g. $\sim 40\%$ of total DM energy density. In summary $M_1 \approx 2$ keV is allowed by the present constraints and $\theta_1'^2$ is allowed to reach $\sim 10^{-6}$ [2].

We note that ν'_{R2} has very small Yukawa coupling and can not come into thermal equilibrium due to this interaction. Other interaction of ν'_{R2} is needed to make it populated at temperature of electro-weak scale. Detailed model for it will be explored in future works. The example shown is a particular case with normal hierarchy. The quasi-degenerate mass pattern of light neutrinos would give too large mixing of keV scale right-handed neutrino with active neutrinos and is not compatible with the ν SM [1, 15]. For inverted mass hierarchy, we can choose matrix O as

$$O = \begin{pmatrix} 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \\ 1 & 0 & 0 \end{pmatrix}. \quad (23)$$

Similar results can be obtained in the case that two GeV scale $\nu_{R2,3}$ are degenerate.

ν_{R1} capture by radioactive nuclei: ν_{R1} can interact with SM particles through mixing with active neutrinos. The four-Fermion interaction of ν_{R1} with electron is

$$\begin{aligned} \Delta L &= \frac{G_F}{\sqrt{2}} R_{e1}^* \bar{n} \gamma^\mu (g_A - \gamma_5 g_A) p \\ &\times \bar{\nu}_{R1} \gamma_\mu (1 - \gamma_5) e + h.c., \end{aligned} \quad (24)$$

where n and p stand for neutron and proton. $g_{V,A}$ are vector and axial-vector form factors. According to Eq. (24) ν_{R1} DM in the universe can be captured by radioactive nuclei in processes

$$\nu_{R1} + A \rightarrow B^- + e^+ \quad \text{or} \quad \nu_{R1} + A \rightarrow B^+ + e^-. \quad (25)$$

The energy of electron produced in this process is

$$E_e = m_e + Q_\beta + M_1, \quad (26)$$

where Q_β is the end point kinetic energy of the beta decay ($A \rightarrow B^+ + e^- + \bar{\nu}_e$) or anti-beta decay ($A \rightarrow B^- + e^+ + \nu_e$). For $M_1 \ll Q_\beta$, the cross section of this process is similar to

that of the capture of the cosmic relic neutrinos [24, 25]. The capture of ν_{R1} DM produces mono-energetic electrons beyond the end point of the spectrum of beta decay or anti-beta decay. For super-allowed transition the cross section is

$$\sigma_{capt}v_\nu = \frac{\pi^2 \ln 2}{f t_{1/2}} p_e E_e F(Z, E_e) |R_{e1}|^2, \quad (27)$$

where $p_e = \sqrt{2m_e(Q_\beta + M_1)}$ and $F(Z, E_e)$ is the Fermi function. In Eq. (27) a factor of $1/2$ arising from the Majorana nature of ν_{R1} has been included. The cross section is normalized to the beta decay rate using $t_{1/2}$, the half-life of A nucleus and the factor f

$$f = \int_{m_e}^{m_e + Q_\beta} F(Z, E'_e) p'_e E'_e E'_\nu p'_\nu dE'_e. \quad (28)$$

p'_e, E'_e are momentum and energy of electron (or positron). p'_ν and E'_ν are the momentum and energy of anti-neutrino (or neutrino) in beta decay (or anti-beta decay).

Consider ν_{R1} capture by Tritium: $\nu_{R1} + {}^3\text{H} \rightarrow {}^3\text{He} + e^-$ which has $Q_\beta = 18.59$ keV and $t_{1/2} = 12.3$ year. Using parameters in [24] we find that for $M_1 \ll Q_\beta$ the cross section of this process is $\sigma_{capt}v_\nu \approx 3.9 \times 10^{-45} \text{ cm}^{-2} \times c \times |R_{e1}|^2$ where c is the speed of light. The event rate, $\sigma_{capt}v_\nu n_{\nu_{R1}}$, is estimated

$$N \approx 0.71 \text{ year}^{-1} \times \frac{n_{\nu_{R1}}}{10^5 \text{ cm}^{-3}} \frac{|R_{e1}|^2}{10^{-6}} \frac{{}^3\text{H}}{10 \text{ kg}}, \quad (29)$$

where ν_{R1} DM is assumed to account for a significant part of DM and its number density is estimated

$$n_{\nu_{R1}} \sim 10^5 \text{ cm}^{-3} \frac{\rho_{\nu_{R1}}}{0.3 \text{ GeV cm}^{-3}} \frac{3 \text{ keV}}{M_1}. \quad (30)$$

In Eq. (30) we have used reference density 0.3 GeV cm^{-3} , the estimated DM density in the galactic halo at the position of the solar system. This estimation of local density is extrapolated from the astrophysical observation of Milky Way and the model of DM halo which does not depend on whether the DM is warm or is cold. This estimation is applicable to warm DM.

We find that ${}^{106}\text{Ru}$, which has $Q_\beta = 39.4$ keV and $t_{1/2} = 373.6$ days, is also good to detect ν_{R1} . The cross section of ν_{R1} capture by ${}^{106}\text{Ru}$ is $\sigma_{capt}v_\nu \approx 2.94 \times 10^{-45} \text{ cm}^{-2} \times c \times |R_{e1}|^2$ for $M_1 \ll Q_\beta$. The event rate of ν_{R1} capture is

$$N \approx 16 \text{ year}^{-1} \times \frac{n_{\nu_{R1}}}{10^5 \text{ cm}^{-3}} \frac{|R_{e1}|^2}{10^{-6}} \frac{{}^{106}\text{Ru}}{10 \text{ Ton}}. \quad (31)$$

We note that the production rate of ^3H in reactor is 0.01% and the production rate of ^{106}Ru is 0.4%. If 10 kg Tritium are produced per year in reactors, around 12 Tons of ^{106}Ru are produced. We note that the reference number Eq. (30) used in Eq. (31) is a conservative estimate of the local number density. It's possible that the solar system is located in a sub-halo in which the local DM density is several orders of magnitude larger than the galactic value. If this happens, capture rate is several orders of magnitude larger.

We emphasize that the events of ν_{R1} capture are mono-energetic electrons which have energy well separated from the β decay spectrum. The background of the β decay events does not affect the detection of ν_{R1} . Moreover, this experiment does not require measurement of very high precision as in KATRIN [27] or in detecting cosmic background neutrinos [24, 25]. Rather than using gaseous Tritium in KATRIN, large volume of ^3H or ^{106}Ru target in solid state can be used in ν_{R1} capture experiment. This experiment might be done in the near future. We note that future X-ray observation may improve the constraint on $\theta_1'^2$ which will reduce the expected event rate of ν_{R1} capture. However the scenario of keV scale right-handed neutrino as DM candidate is hard to be ruled out and the DM capture by radioactive nuclei proposed in this article is one way to detect this keV scale DM candidate.

We note that background events of the capture of solar pp neutrinos are negligible. According to the standard solar model the flux of pp neutrinos of energy $\lesssim 10$ keV is about $8. \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ [26] and the corresponding density of these pp neutrinos is about $2.7 \times 10^{-4} \text{ cm}^{-3}$. The event rate of the capture of pp neutrinos of energy $\lesssim 10$ keV is $\sim 4.0 \times 10^{-3} \text{ year}^{-1}$ for 10 kg of Tritium and is $\sim 8.5 \times 10^{-2} \text{ year}^{-1}$ for 10 ton of ^{106}Ru . Effects of low energy solar neutrinos can be neglected in discussing the capture of ν_{R1} DM.

Recent analysis of X-ray observations of local dwarf Willian 1 show evidence that the ν_{R1} DM may have mass around 5 keV with mixing $|R_{l1}|^2 \lesssim 10^{-9}$ [28]. Another analysis of the X-ray observation of the galactic center suggests that ν_{R1} DM has mass around 17 keV with mixing $|R_{l1}|^2 \sim 10^{-12}$ [29]. This small neutrino mixing would give too small event rates of ν_{R1} capture by radioactive nuclei unless we are living in a sub-halo of DM.

Conclusion: In conclusion we have considered several issues of the keV scale right-handed ν_{R1} DM in the νSM . We have shown that a GeV scale right-handed neutrino in

the ν SM can have sufficient small couplings to active neutrinos and its decay can lead to large amount of entropy release (~ 100) at MeV temperature scale. This happens when two GeV scale right-handed neutrinos are degenerate. Two degenerate right-handed neutrinos in their interaction base can have very different strengths of couplings with active neutrinos and a large suppression to the Yukawa couplings of one of the GeV scale ν_R 's can be achieved. Mass and mixing of light neutrinos can be correctly explained in the model considered. Density of ν_{R1} DM can be diluted by a factor larger than 100 in the reheating produced by the decay of this GeV scale right-handed neutrino. The mixing of ν_{R1} with active neutrinos is allowed to be as large as $\theta_1^2 \sim 10^{-6}$ for $M_1 \approx 2$ keV, reaching the bound from X-ray observation.

We have discussed the capture of the cosmic background of keV scale ν_{R1} DM by radioactive nuclei ^3H and ^{106}Ru . ν_{R1} capture produces events of mono-energetic electrons with keV scale energy away from the beta decay spectrum. The background of beta decay events does not affect the detection of ν_{R1} capture events and this experiment does not require measurement of very high precision as in experiment of direct measurement of neutrino mass or in detecting cosmic background neutrinos. Rather than using gaseous Tritium in experiment of direct measurement of neutrino mass, large volume of ^3H or ^{106}Ru target in solid state can be used in ν_{R1} capture experiment. We find that there are about 0.7 events per year on 10 kg tritium target and about 16 events per year on 10 Ton ^{106}Ru target for mixing $|R_{e1}|^2 = 10^{-6}$ and $n_{\nu_{R1}} = 10^5 \text{ cm}^{-3}$.

We comment that if we are living in a sub-halo of DM the event rate can be much larger. Two examples with ^3H and ^{106}Ru targets are related to beta decay. It is interesting if suitable radioactive nucleus can be found to do ν_{R1} capture in anti-beta decay experiment. We emphasize that detecting ν_{R1} DM on radioactive nuclei is a new type of experiment for detecting DM in the universe. It is very interesting if other radioactive nucleus, better than ^3H and ^{106}Ru , can be found. This radioactive nucleus should have reasonable lifetime, large enough capture rate and reasonably large production rate in reactors or is available in nature. It's worth further exploration.

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